CYLINDERS HAVING DIFFERING SURFACE ROUGHNESS

CROSS-REFERENCE

[0001] This application claims priority to German patent application no. 103 02 107.8 filed January 21, 2003, the contents of which are incorporated by reference as if fully set forth herein.

TECHNICAL FIELD

[0002] The present invention relates to cylinders having a first cylinder surface of a first surface roughness and a second cylinder surface of a second surface roughness. Such cylinders may be advantageously utilized in reciprocating piston engines, such as internal combustion engines (e.g. two-cycle and four-cycle engines), reciprocating piston compressors and reciprocating piston pumps.

RELATED ART

[0003] It is known to treat the surface of a cylinder liner or cylinder face (i.e., the cylinder surface) in order to obtain a specific surface roughness. Such surface treatments include plating, vapor depositing, etching, blasting and honing techniques. For example, U.S. Patent No. 6,244,934 teaches cylinders having a uniform surface roughness prepared by a blasting technique. In addition, U.S. Patent No. 6,309,806 teaches cylinders having an increased surface roughness at the position where the piston "turns over," which cylinder surfaces are prepared using an etching technique.

[0004] During the operation of an internal combustion engine (e.g., a four cycle engine), the piston reciprocates within the cylinder between a top dead point of the piston and a bottom dead center of the piston. The combustion space above the piston is sealed by one or more piston rings that slide along the cylinder surface while providing a sealing contact between the cylinder surface and the piston. In order to prevent the piston from seizing during operation, it is necessary to continuously lubricate the piston rings and the cylinder surface by preferably forming a lubricating film on the cylinder surface. The formation of such a lubricating film is supported by a certain roughness of the cylinder surface, which roughness provides a plurality of small oil reservoirs (pockets) on the cylinder surface. These oil reservoirs retain and supply the lubricating oil to form the lubricating film.

[0005] German Patent Publication No. 196 05 558 A1 discloses a method for processing a cylinder surface of internal combustion engines, in which the cylinder surface is honed,

except for the portions of the cylinder surface that contact the piston rings at the top dead point and the bottom dead point of the piston. The un-honed portions are processed using a lapping technique to form plateaus and valleys along portions of the cylinder surface that contact the piston rings at the top dead point and the bottom dead point of the piston.

[0006] German Patent No. 42 38 525 C1 discloses a cylinder surface having a wear protection layer. More particularly, a hard chromium layer is provided only on the portion of the cylinder surface that contacts the top piston ring of the piston when the piston is positioned at its top dead point.

[0007] US Patent Nos. 5,415,761 and 6,319,385 disclose methods for electrochemically depositing a surface coating so as to form a structured surface.

SUMMARY OF THE INVENTION

[0008] It is an object of the present invention to provide improved cylinder surfaces and methods for making and using the same.

[0009] In one aspect of the present teachings, a cylinder of a reciprocating piston apparatus preferably includes a first cylinder surface region having a first surface roughness and a second cylinder surface region having a second surface roughness. The first cylinder surface region is defined at least in part by the contact area between the reciprocating piston (i.e., the piston rings disposed around the reciprocating piston) and the cylinder surface when the reciprocating piston is disposed at its top dead point. The second cylinder surface region is preferably defined at least in part by the surface area that is adjacent to the first cylinder surface region on the side of the bottom dead point of the reciprocating piston. Preferably, the first surface roughness is less than the second surface roughness.

[0010] In another aspect of the present teachings, the first cylinder surface region preferably comprises a hard chromium layer and the second cylinder surface region preferably comprises a topochromium layer. The hard chromium layer and the topochromium layer may preferably comprise the same composition of elements and additives. However, the topochromium layer is characterized by having a generally rougher surface than the hard chromium layer, which rougher surface is preferably characterized by generally semi-spherical protrusions that define pockets or reservoirs therebetween. The hard chromium layer is preferably smoother in order to provide a tight seal between the reciprocating piston and the cylinder wall when the piston is disposed approximately at the top dead point of the reciprocating piston.

[0011] The top dead point is characterized as the position where the cylinder space (combustion chamber) between the piston and one or more valve communicating with the cylinder space is at a minimum and where the movement of the piston begins to reverse away from the one or more valves. In internal combustion engines, the cylinder is typically subjected to the highest pressure within the cylinder space (combustion chamber) shortly after the piston has reached its top dead point (i.e., shortly after the fuel/air mixture is ignited, which typically occurs just before the piston reaches its top dead point).

[0012] The present cylinders may be advantageously utilized in any type of structure which utilizes a piston that maintains sliding contact with a cylinder wall and more preferably in applications in which the pressure within a cylinder bore (e.g., a combustion chamber) varies. Representative but non-limiting examples include engines, compressors and pumps that utilize reciprocating pistons. It is particularly preferred to utilize the present teachings in diesel engines, including turbo diesel engines, which operate under much higher compression ratios than gasoline engines. The present teachings can be utilized to improve fuel efficiency of diesel engines, and especially turbo diesel engines, by improving the sealing and lubricating performance of the piston/cylinder system.

[0013] Further objects, aspects and advantages of the present teachings will be readily understood after reading the following description with reference to the drawings and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Fig. 1 shows a partial, cross-sectional view of a representative cylinder having a cylinder surface with a surface roughness that differs along the length of the cylinder wall, and a piston that reciprocates within the cylinder.

[0015] Fig. 2 shows a cross-sectional view of a representative cylinder liner according to the present teachings that may be separately manufactured and then inserted into a cylinder bore.

DETAILED DESCRIPTION OF THE INVENTION

[0016] In one embodiment of the present teachings, a first cylinder surface region may have a first surface roughness, which first cylinder surface region preferably includes at least a portion of the cylinder surface that is adapted to contact a reciprocating piston (and/or one or more piston rings disposed around the piston) when the reciprocating piston is positioned at its top dead point. Preferably, a hard chromium layer is disposed on the first cylinder surface

region. In addition, a second cylinder surface region may be provided with a second surface roughness, which second cylinder surface region is preferably adapted to contact the reciprocating piston (and/or one or more piston rings disposed around the piston) when the reciprocating piston is disposed at its bottom dead point. Preferably, a topochromium layer may be disposed on the second cylinder surface region and the second cylinder surface region is rougher than the first cylinder surface region.

[0017] In one advantageous embodiment, the first surface roughness is preferably in the range of about Rz 1-20 microns and/or the second surface roughness is preferably in the range of about Rz 4-50 microns.

[0018] The roughness of the second cylinder surface region may optionally increase in the direction from the first cylinder surface region towards the bottom dead point of the reciprocating piston. In addition or in the alternative, the roughness in the first cylinder surface region may optionally increase in the direction from the top dead point towards the second cylinder surface region. In either or both cases, the roughness may increase continuously, stepwise or both.

[0019] In other advantageous embodiments, the cylinder wall and the reciprocating piston preferably define a compression chamber and the cylinder wall and the reciprocating piston are arranged and constructed to withstand a pressure of at least about 80 bar within the compression chamber, more preferably at least about 100 bar and most preferably at least about 120 bar. A preferred, but not limiting, pressure range is between about 80-140 bar within the compression chamber.

[0020] In other advantageous embodiments, the first cylinder surface region may extend along at least 5% of a total length of a sliding path defined between the position of an upper piston ring when the piston is disposed at its top dead point and the position of a lower piston ring when the piston is disposed at its bottom dead point. More preferably, the first cylinder surface region may extend along at least 40% of the total length of the sliding path, such as about 40-80% of the total length of the sliding path.

[0021] Each of the additional features and teachings disclosed below may be utilized separately or in conjunction with other features and teachings to provide improved cylinders and cylinder liners and methods for designing and using the same. Representative examples of the present invention, which examples utilize many of these additional features and teachings both separately and in combination, will now be described in further detail with reference to the attached drawings. This detailed description is merely intended to teach a

person of skill in the art further details for practicing preferred aspects of the present teachings and is not intended to limit the scope of the invention. Therefore, combinations of features and steps disclosed in the following detail description may not be necessary to practice the invention in the broadest sense, and are instead taught merely to particularly describe representative examples of the present teachings.

[0022] Moreover, the various features of the representative examples and the dependent claims may be combined in ways that are not specifically and explicitly enumerated in order to provide additional useful embodiments of the present teachings. In addition, it is expressly noted that all features disclosed in the description and/or the claims are intended to be disclosed separately and independently from each other for the purpose of original disclosure, as well as for the purpose of restricting the claimed subject matter independent of the compositions of the features in the embodiments and/or the claims. It is also expressly noted that all value ranges or indications of groups of entities disclose every possible intermediate value or intermediate entity for the purpose of original disclosure, as well as for the purpose of restricting the claimed subject matter.

[0023] FIG. 1 shows a cross-section of a portion of a cylinder wall 1, which optionally may be utilized in engines, compressors or pumps. Optionally, the cylinder wall 1 may be part of a cylinder liner that is formed separately from an engine block. The cylinder liner can be inserted into a space defined within the engine block for the cylinder in order to provide the cylinder surface that is adapted to contact piston 2 (or more specifically, piston rings 3, 4).

[0024] Piston 2 is illustrated in the position of its top dead point TDP. However, during operation, the piston 2 reciprocates between its top dead point TDP and its bottom dead point BDP. The bottom dead point BDP of the piston 2 is illustrated with broken lines and indicated by reference numeral 2'. Two piston rings 3, 4 are disposed around the piston 2 in the representative example, although the number of piston rings 3, 4 may be changed according to design requirements.

[0025] When the piston 2 is disposed at the top dead point TDP, the gas (e.g., a fuel/air mixture for engine applications) disposed within the compression chamber 7 (e.g., a combustion chamber of an internal combustion engine) is compressed to the highest degree or is already ignited such that the pressure to be sealed by the piston rings 3, 4 is essentially at its highest level. On the other hand, when the piston 2 is disposed at the bottom dead point BDP, the pressure within the compression chamber 7 is essentially at its lowest level. Consequently, the pressure sealed by the piston rings 3, 4 decreases continuously, or

substantially continuously, as the piston 2 moves from the top dead point TDP to the bottom dead point BDP (i.e., during the working or expansion stroke). During the compression stroke and during an exhaust stroke (i.e., when the piston 2 moves from the bottom dead point BDP to the top dead point TDP), the pressure increases continuously or substantially continuously. Thus, as noted above, the highest or largest pressure to be sealed is, generally speaking, generated when the piston 2 has moved to the area of the top dead point TDP.

[0026] The surface roughness of the cylinder wall 1 in the area of the top dead point TDP preferably is relatively low. In other words, the surface of cylinder wall 1 around the top dead point TDP is preferably relatively smooth and is preferably smoother than other portions of the cylinder surface, as will be further discussed below. In particular, in the area around the height H1 shown in FIG. 1, which area corresponds to the region opposing the upper piston ring 3 when the piston 2 is disposed at its top dead point TDP, the cylinder surface is particularly smooth in order to provide a tight seal between the piston rings 3, 4 and the cylinder wall 1 at the top dead point TDP. It is understood that smoother surfaces (i.e., low surface roughness) enable tight sealing of higher pressures. If the surface roughness is too large in the area around H1, the piston rings 3, 4 cannot maintain a sufficient seal with the cylinder wall 1 so as to maintain the high pressure in the compression space 7 at the intended level.

[0027] According to the present teachings, the cylinder wall 1 preferably comprises a first cylinder surface region 5 defined along the inner surface of the cylinder wall 1, which inner surface faces or opposes the piston 2. More particularly, the first cylinder surface region 5 preferably includes at least the surface area of the cylinder wall 1 that faces (opposes) the uppermost piston ring 3 when the piston 2 is disposed at its top dead point TDP. In addition, the first cylinder surface region 5 preferably extends along a predetermined distance of the cylinder wall 1 towards the bottom dead point BDP, which predetermined distance will be explained in greater detail below. Furthermore, the first cylinder surface region 5 has a first surface roughness Ra1 or Rz1, as will be defined below.

[0028] A second cylinder surface region 6 preferably extends from the first cylinder surface region 5 towards the bottom dead point BDP and, preferably but not necessarily, may extend beyond the bottom dead point BDP. More particularly, the second cylinder surface region 6 preferably extends at least to the surface area of the cylinder wall 1 that faces (opposes) the lowermost piston ring 4 when the piston 2 is positioned at its bottom dead point BDP (i.e., at least down to the height H5 shown in FIG. 1). Furthermore, the second cylinder surface

region 6 preferably has a second surface roughness Ra2 or Rz2, which second surface roughness Ra2 (Rz2) is greater (i.e., less smooth or rougher) than the first surface roughness Ra1 (Rz1).

[0029] In the representative embodiment shown in FIG. 1, the second cylinder surface region 6 comprises three sub-regions 6a, 6b, 6c that extend in the direction from the top dead point TDP towards the bottom dead point BDP and beyond the same. The three sub-regions 6a, 6b, 6c are preferably adjacent (contiguous) to each other, although such arrangement is optional according to the present teachings.

[0030] Optionally, the surface roughness of the cylinder wall 1 may generally and/or gradually increase along the sub-regions 6a, 6b, 6c from the top dead point TDP to the bottom dead point BDP. In other words, first sub-region 6a may be smoother (less rough) than second sub-region 6b, which is in turn may be smoother (less rough) than third sub-region 6c. For example, the first sub-region 6a, which is preferably defined between the heights H2 and H3 in FIG. 1, may have a first surface roughness Ra2'. The second sub-region 6b between H3 and H4 may have a second surface roughness Ra2" that is greater than the first surface roughness Ra2'. In addition, the third sub-region 6c between H4 and H6 may have a third surface roughness Ra2'" that is greater than the second surface roughness Ra2". However, it is also possible for the entire first cylinder surface region 5 to have substantially the same first surface roughness and the entire second cylinder surface region 6 may have substantially the same second surface roughness.

[0031] As a result of such constructions, lubrication performance can be improved along the length of the cylinder wall 1 by providing a greater number of and/or larger oil reservoirs in the region of the cylinder wall 1 adjacent to and including the bottom dead point BDP of the piston 2. In addition, by decreasing the percentage or amount of contact area between sliding contact points of the cylinder wall 1 and the piston rings 3, 4, the friction between the cylinder wall 1 and the piston rings 3, 4 can be reduced in such reduced contact area(s). In other words, a portion of the cylinder surface that is rougher will have a decreased contact area with the piston rings 3, 4, as compared to a portion or region of the cylinder surface that is smoother.

[0032] In addition, by increasing the surface roughness of the cylinder wall 1 and forming a plurality of oil reservoirs in the cylinder wall 1, which oil reservoirs will retain or hold lubricating oil during operation, a greater volume of lubricating oil contacts the cylinder wall 1 for a longer period of time. As a result, the cooling effect of the lubricating oil can be

increased. Furthermore, these oil reservoirs provide a ready source of lubricating oil for forming the lubricating film along the cylinder wall 1, which lubricating oil can be readily transferred (moved) from the rougher surfaces to the smoother surfaces (i.e., portions of the cylinder wall 1 having smaller or negligible oil reservoirs) due to the oil spreading effect provided by the piston rings 3, 4 moving along the cylinder wall 1.

[0033] Thus, the present teachings generally provide an advantageous construction, in which a relatively smooth surface is provided for the cylinder wall 1 in the area or region (i.e., in the TDP position) where the highest pressure must be sealed. On the other hand, a relatively rougher surface is provided for the cylinder wall 1 in the area or region (i.e., the BDP position) where the lowest pressure must be sealed. The rougher surface provides increased capacity for retaining lubricating oil in the small oil reservoirs created by the rougher surface, thereby improving lubrication and cooling effects without significantly affecting the sealing performance of the cylinder. Thus, the present teachings provide an advantageous compromise between sealing performance and lubricating performance for applications that utilize a reciprocating piston.

[0034] In another aspect of the present teachings, a sliding path may be defined between (i) the upper edge of the uppermost piston ring 3 of the piston 2 when the piston 2 is positioned at its top dead point TDP (i.e., the height H1) and (ii) the lower edge of the lowermost piston ring 4 of the piston 2 when the piston 2 is positioned at its bottom dead point BDP (i.e., the height H5). Preferably, the first cylinder surface region 5 comprises at least 5% of this sliding path. For example, the first cylinder surface region 5 may cover about 5-40% of the sliding path and more preferably, about 15-25%. However, in other applications, it may be desirable to have the first cylinder surface region comprise more than 40% of the sliding path, such as about 50%, 60%, 70% or 80%. Thus, in an alternative embodiment, the first cylinder surface region 5 preferably covers at least 40% of the sliding path and more preferably between about 40-80% of the total sliding path, as was defined above. More precise values can be empirically determined based upon the pressure to be sealed at the top dead point TDP, the materials selected to form the cylinder wall 1 and the piston rings 3, 4 and the first surface roughness.

[0035] In another preferred aspect of the present teachings, the first surface roughness is in the range of about Ra 0.05 to 0.3 microns or about Rz 1-20 microns. The second cylinder surface region includes at least a portion of the remaining part of the sliding path. Preferably,

the second surface roughness is in the range from about Ra 0.3 to 5 microns or about Rz 4-50 microns.

[0036] Herein, the values of "Ra" are defined by German standard D4768, T1: 8.74. "Ra" is the height of a rectangle defined by having the same area as the sum of all roughness profiles of the cylinder surface that are above a middle line, which middle line forms the bottom side or leg of the rectangle. The middle line is determined as being one-half of the arithmetic mean peak-to-valley distance of the surface profiles. Thus, the Ra values described and claimed herein are determined according to this standard calculation, which is incorporated herein by reference.

[0037] The values of "Rz" are also defined by German standard D4768, T1: 8.74. "Rz" is the arithmetic mean of the maximum peak-to-valley distances defined within each five (5) adjacent measuring intervals (distances). In other words, 5 adjacent intervals are identified and the highest peak and lowest valley within each interval are determined. The difference between the highest peak and lowest valley are calculated for each of the 5 adjacent intervals and then the arithmetic mean (average) of these peak-to-valley distances is calculated for the 5 adjacent intervals. Again, the Rz values described and claimed herein are determined according to this standard calculation, which has been incorporated herein by reference.

[0038] According to a presently preferred embodiment of the present teachings, the transition (change) of the surface roughness from the first cylinder surface region 5 to the second cylinder surface region 6 is abrupt, but continuous or substantially continuous. In other words, the surface roughness along the transition area changes substantially continuously, but in a relatively substantial amount. However, the transition of the surface roughness from the first cylinder surface region 5 to the second cylinder surface region 6 may be step-wise (i.e., substantially discontinuous).

[0039] While the first cylinder surface region 5 preferably has the same surface level, or substantially the same surface level, as the second cylinder surface region 6, the step (i.e., change in the surface level) along the transition area is preferably less or smaller than about 0.01 mm, more preferably less or smaller than about 0.001 mm (1 micron) and most preferably less or smaller than about 0.4 micron. In order to provide a constant or uniform surface level for contacting the piston rings 3, 4, it is preferable to minimize any surface level differences between the first cylinder surface region 5 and the second cylinder surface region 6.

[0040] In one application of the present teachings, the surface roughness of the first cylinder surface region 5 may be constant or substantially constant across the entire first cylinder surface region 5. However, in one modification of the present teachings, the surface roughness of the first cylinder surface region 5 may preferably change (increase) continuously, or substantially continuously, along the direction from the top dead point TDP to the bottom dead point BDP. Further, the surface roughness may changes (increase) continuously or substantially continuously within the second cylinder surface region 6 towards the bottom dead point BDP (and optionally extending beyond the BDP) or may be substantially uniform along the entire second cylinder surface region 6. Thus, the surface roughness of the cylinder wall 1 can be suitably adapted to the continuously decreasing pressure experienced as the piston 2 moves from the TDP to the BDP.

[0041] Cylinder surfaces according to the present teachings preferably may be formed by depositing a chromium layer on the cylinder wall 1 using an electrochemical (galvanic) method, such as described in US Patent Nos. 5,415,761 and 6,319,385, the contents of which are incorporated by reference as if fully set forth herein.

[0042] The first cylinder surface region 5 preferably comprises a "hard" chromium layer, which may be deposited using known methods. A "hard" chromium layer generally means a substantially pure layer of chromium having a thickness greater than 5 microns. Representative Vickers hardness values for the hard chromium layer are in the range of about 950-1050. As noted above, the first cylinder surface region 5 preferably has a surface roughness in the range of Ra 0.05 to 0.3 microns (micrometers). If the surface roughness increases in the direction from the TDP to the BDP, it is preferred that the increasing surface roughness of the first cylinder surface region 5 falls within the range of Ra 0.05 to 0.3 microns.

[0043] As indicated above, the second cylinder surface region 6 also may be provided with a surface coating according the method described in U.S. Patent No. 6,319,385. However, contrary to the first cylinder surface region 5, the second cylinder surface region 6 is preferably provided with a surface coating that will be called a "topochromium" layer. According to the present teachings, a "topochromium" layer is intended to mean a surface structure comprising essentially of adjacent and superpositioned half sphere-shaped protrusions, in which oil reservoirs or pockets are defined by the valleys or recesses or grooves between the protrusions. In addition, this half sphere form reduces the percentage contact area of the piston rings 3, 4 and the cylinder wall 1. For example, the area of the

cylinder wall 1 contacting the piston rings 3, 4 can be, e.g., about 25% of the total area that faces (opposes) the piston rings 3, 4.

[0044] The second cylinder surface region 6 preferably has a surface roughness that falls within the range of about Ra 0.3 to 5 microns (micrometers). In other words, the surface roughness of each of the sub-regions 6a, 6b, 6c preferably falls within the range of about Ra 0.3 to 5 microns, although the surface roughness optionally may increase, either gradually and continuous or step-wise, from the first sub-region 6a to the third sub-region 6c. Furthermore, sub-regions 6a, 6b, 6c are not essential to the present teachings and one or more the sub-regions 6a, 6b, 6c may be merged with an adjacent sub-region or the surface roughness of the second cylinder surface region 6 may continuously change without discrete or readily discernable changes in roughness.

[0045] The hard chromium layer and the topochromium layer may preferably comprise chromium, e.g., pure chromium, and unavoidable impurities. Preferably, the hard chromium layer and the topochromium layer may have a thickness of about 25 microns. Both layers may be deposited onto a cast-iron, such as nodular cast-iron, or aluminum engine block. In the alternative, a cylinder liner may be formed from cast-iron, such as nodular cast-iron, or aluminum and the chromium layers may be deposited on the cylinder liner. Then, the cylinder liner may be inserted into a cylinder bore defined within a separately formed engine block.

[0046] The hard chromium layer of the first cylinder surface region 5 may be simultaneously deposited with the topochromium layer of the second cylinder surface region 6 according to the methods described by the above-noted US Patent No. 6,319,385. For example, a segmented bar-shaped or rod-shaped electrode (anode) may be used and different potentials/currents, which are necessary to form the different layers, are applied to the different segments.

[0047] More specifically, the electrode segments are preferably electronically isolated or insulated from each other and the rod-shaped electrode is inserted into the cylinder such that the central longitudinal axis of the cylinder and the electrode are co-axial. In order to form the topochromium layer, a step-wise changing current is applied to a first segment of the electrode that faces the second cylinder surface region 6. Further teachings concerning appropriate current waveforms for preparing the topochromium layer are provided in U.S. Patent 6,319,385 and therefore, need not be repeated herein.

[0048] In order to form the hard chromium layer along the first cylinder surface region 5, a constant, or substantially constant current may be applied to a second segment of the electrode that faces the first cylinder surface region 5.

[0049] Preferably, the diameter of the first segment of the electrode is larger than the second segment in order to deposit the adjacent hard chromium layer and topochromium layer at the same height or level. In other words, such an electrode arrangement is intended to minimize or eliminate any step between the surface levels of the hard chromium layer and the topochromium layer. Thus, this representative method can automatically provide a continuous transition of the surface roughness from the first cylinder surface region 5 to the second cylinder surface region 6.

[0050] In the alternative, a continuously increasing surface roughness from the top dead point TDP to the bottom dead point BDP may be formed, e.g., by using a cone-shaped electrode or by using an electrode having a plurality of segments.

[0051] The respective chromium layers preferably have a thickness in the range of between about 10 and 100 μm for the sphere surfaces, more preferably about 20 to 80 μm and most preferably about 20 to 60 μm.

[0052] In one representative example of an application of the present invention, a turbo diesel engine was constructed with cylinder surfaces according to the present teachings. The diesel engine was formed as a cast-iron engine block and the cylinder walls 1 were formed as cylinder liners that were inserted into cylinder bores defined within the cast-iron engine block. Fig. 2 shows an illustration of the constructed example of the present teachings, in which X represents the topochromium layer (second cylinder surface region 6) and Y represents the hard chromium layer (first cylinder surface 5). In addition, it is noted that the piston diameter was 69 mm, the piston stroke length was 62 mm, the cylinders had a volume of 223 cubic centimeters and a compression ratio of 1:22 was utilized. In addition, it is noted that during operation a maximum pressure of 132 bar was observed in the combustion space (i.e., combustion space 7 according to Fig. 1) defined within the cylinder.

[0053] The cylinder liners were prepared by first honing the cylinder surface (cylinder wall 1) to provide a surface roughness of about Rz 3-4 microns. Then, the hard chromium layer was deposited on the cylinder wall 1 to provide a first surface roughness (corresponding to the first cylinder surface region 5) of Rz 2-3 microns and the topochromium layer was deposited on the cylinder wall 1 to provide a second surface roughness (corresponding to the second cylinder surface region 6) of Rz 5-7 microns. The hard chromium layer was deposited using a

first anode (electrode segment) having a diameter of 20-30 mm and a current density of 40 Amps per square decimeter (A/dm^2) was applied to the first anode. The topochromium layer was deposited using a second anode (electrode segment) having a diameter of 30-40 mm and a varying current density between 20-70 Amps per square decimeter (A/dm^2) was applied to the second anode in accordance with the teachings of U.S. Patent No. 6,319,385. The first cylinder surface region 5 having the first surface roughness comprised approximately 78% of the total sliding path of the piston 2, as was defined above. Further, it is noted that the piston rings 3, 4 were not coated with chromium, as is common in the known art.

[0054] This turbo diesel engine, which was constructed according to the present teachings, exhibited a fuel consumption reduction of 3-5% as compared to a similarly constructed turbo diesel engine having the same dimensions, piston stroke length, cylinder volume, compression ratio and maximum pressure. The cylinder liner of the comparative example was prepared as a grey cast-iron cylinder liner having a composition of 2.0% carbon, 1.0% manganese, 0.4% chromium, 2.0% silicon, less than 0.1% sulfur, 0.6% phosphorus, the rest being iron and unavoidable impurities. Further, the surface of the cylinder liner was honed to a roughness within the range of Rz 3-4 microns that was generally uniform over the length of the cylinder surface. Further, the piston rings of the comparative example were coated with chromium.

[0055] Thus, the present teachings are particularly advantageous when utilized in diesel engines, and more preferably turbo diesel engines, due to the relatively high pressures that are generated within the compression/combustion chamber of the cylinder. Generally speaking, the pressure within the cylinder of a diesel engine may exceed 80 bar, such as between 90-100 bar for normal diesel engines and between 120-140 bar for turbo diesel engines. By providing a relatively smooth surface in the first cylinder surface region 5 (i.e., at and about the TDP position), a tight seal can be obtained for such high pressures. However, by providing a higher surface roughness near the BDP position (i.e., in the second cylinder surface region 6), improved lubrication is possible. The combination of these two effects appears to have provided the notably increased fuel efficiency of the constructed example of the present teachings.